

# Chapter 1

## Introduction

This dissertation analyzes observations and simulations of precipitating tropical cloud systems associated with deep atmospheric convection over the tropical Indian Ocean during the winter monsoon season. Such cloud systems are representative of the most energetic disturbances in the tropical atmosphere. The intense vertical motions occurring in their convective cores form the upward branch of the overturning flow that characterizes the general circulation of the tropical atmosphere. Condensed water, in the form of cloud material and precipitation provides the link between the sunlight that is ultimately responsible for oceanic and atmospheric dynamics, and heating gradients in the lower atmosphere that cause observed weather patterns. Because of the pivotal role of cloud systems in present climate, their representation in global climate models is a central point of debate in the pursuit of accurate and precise predictions of climate change.

Projections of the increase in global-averaged surface temperature over the next 100 years due to increasing greenhouse gas emissions vary from +1.4 °C to +5.8 °C based on global climate model simulations (Houghton et al. 2001). Variations in projected warming result from, among other things, uncertainties in the amount of future greenhouse increases, as well as uncertainties in the thermodynamic impacts of aerosols. However, a 1989 study of 14 climate models indicated that the greatest source of model-to-model variation in sensitivity to climate change results from differences in the representations of cloud processes and the feedback between clouds and climate (Cess et al. 1989). With regard to the development of cloud-climate research since then, the 2001 assessment report of the Intergovernmental

Panel on Climate Change concluded: “Although there has been clear progress in the physical content of the models, clouds remain a dominant source of uncertainty...” (Houghton et al. 2001).

The release of condensational heating within clouds, together with cloud/radiation interactions, determine in large part the general circulation of the atmosphere. These processes are together referred to as the thermodynamic forcing of a cloud and are the principal means by which cloud systems impact the thermal structure of the atmosphere. Among the challenges facing the climate modeling community are appropriately representing the thermodynamic forcing of cloud systems and predicting any shifts in the distribution of cloud forcing resulting from changes such as increasing greenhouse gas loading.

Satellite data provide an enormous amount of useful data on the structure and dynamics of clouds. While satellite observations have been used in the development and validation of model simulations of cloud processes, these data are typically averaged in time and space over stationary grids. Such Eulerian averaging can mask the relationship between the structure of cloud systems and their effects on the environment. Recognizing this limitation, several studies (Williams and Houze 1987; Machado and Rossow 1993; Boer and Ramanathan 1997) have initiated the Lagrangian approach of tracking clouds as individual objects. The present work extends the Lagrangian approach to unravel the following issues:

- the scale dependence of precipitation and associated latent heating,
- the scale dependence of cloud radiative forcing, and
- the scale dependence of the removal of pollution in the atmosphere.

Observations of cloud scales and scale dependent forcing are compared directly to simulated clouds in a global climate model for the purpose of testing the representation of tropical cloud systems in the model. This is accomplished by applying the same Lagrangian analysis to model output.

The study presented in chapter 3 indicates that the thermodynamic forcing of cloud systems depends strongly upon the spatial scales of cloud systems. This study also explores the relationship between the spectrum of naturally occurring cloud scales and the artificial separation between small clouds and large clouds imposed on atmospheric simulations by model grids of various resolutions. Many important cloud processes occur at scales smaller than a model grid cell. However, in the tropics they conspire to generate overcast decks of cloud spanning 10s of millions of square kilometers. Such decks span numerous grid cells in even coarse grid atmospheric simulations and are therefore identifiable in model output. The dependence of cloud forcing upon the scale of cloud systems is not explicitly simulated and must emerge from the model representation of cloud processes. Observations of scale dependent properties may therefore be exploited as a means of testing simulations of clouds in climate models. Such a validation is carried out in chapter 4 resulting in the identification of several important biases in the representation of precipitating tropical cloud systems. A key finding of the study in chapter 4 is that both the spatial and temporal distribution of tropical precipitation differ substantially in the model simulation from the observed distribution. The potential impacts of such a bias are many; one being that the removal rate of aerosol particles from the atmosphere may be improperly simulated. This is the subject of chapter 5.

The principal tools of this dissertation are satellite measurements of cloud properties and precipitation. Observations from the Tropical Rainfall Measuring Mission (TRMM) satellite are used extensively. TRMM is noteworthy because it is the first satellite mission that provides simultaneous measurements of both precipitation and cloud radiative forcing, the two primary thermodynamic influences of cloud systems. Also used are cloud cover observations from the METEOSAT-5 geosynchronous satellite, which affords better temporal sampling than TRMM. Automated image processing tools have been developed as part of this dissertation project that identify the boundaries of cloud and precipitation structures,

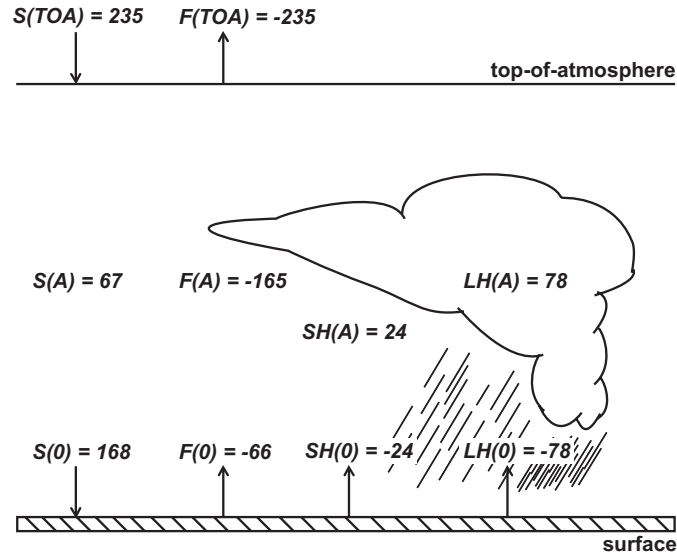
evaluate their sizes, compute the magnitudes of thermodynamic forcing averaged over the area of each structure, and track cloud systems as they evolve through consecutive satellite images. The result is a novel analysis technique that is the basis of the studies presented in chapters 3 and 4. In these studies, ensembles comprising thousands of clouds are assembled from which a statistical description of the spectrum of cloud system scales is constructed and the scale dependence of cloud thermodynamic forcing is evaluated. The description of natural cloud systems that emerges from these analyses is then compared with simulations of tropical cloud systems in a modern atmospheric general circulation model (GCM), the National Center for Atmospheric Research Community Climate Model (NCAR CCM3), and a derivative of CCM3 used for aerosol and trace gas chemistry studies called the Model for Atmospheric Transport and Chemistry (MATCH).

The remainder of this chapter explains in more detail the context for the dissertation, beginning with the paramount role of clouds in the atmosphere-surface energy budget. This is followed by a description of the important structural elements of precipitating tropical cloud systems and a discussion of the representation of cloud systems in modern simulations of the global atmosphere.

## **1.1 Energy budgets of the atmosphere and surface**

In the simplest terms, the dynamics of the ocean and atmosphere are motivated by the equator-to-pole gradient in solar heating. On average the Earth receives  $235 \text{ W m}^{-2}$  of solar (or shortwave) energy, with far more impinging on the tropics than poles. Assuming the planet is in approximate equilibrium, it must emit back to space a comparable amount of energy in the form of terrestrial infrared radiation (also called longwave or heat radiation). The latitudinal variation of infrared radiation, however is much smaller, resulting in an excess of heat in the tropics that must be transported poleward by oceanic and atmospheric dynamics.

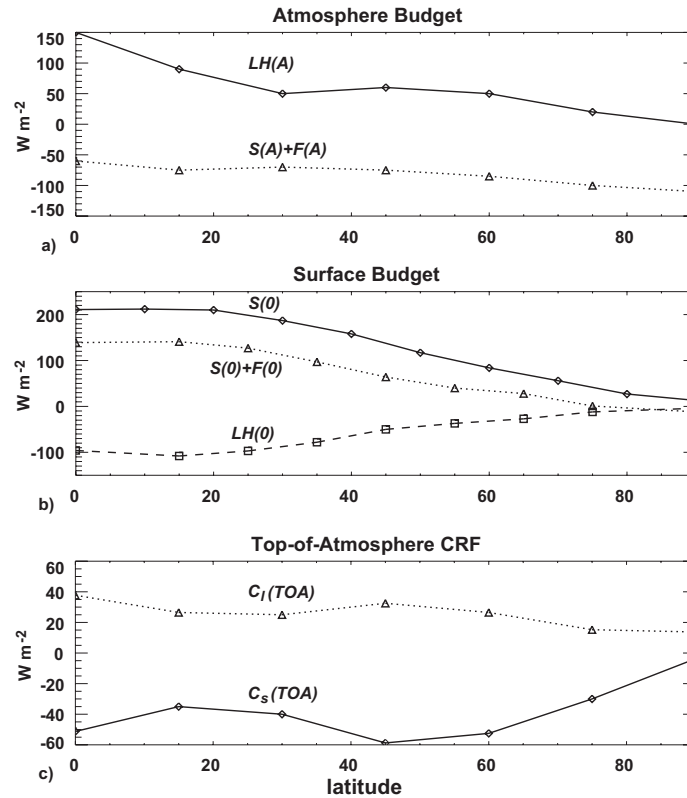
Though the energy for atmospheric dynamics originates at the sun, the atmosphere



**Fig 1.1.** Top of the atmosphere (TOA), atmosphere (A), and surface (0) global annual averaged energy budget terms, including net shortwave flux (S), net longwave flux (F), sensible heat (SH) and latent heat (LH). Units are  $\text{W m}^{-2}$  (values from Kiehl and Trenberth 1997).

is largely transparent to solar radiation, implying that additional processes are required to transfer solar radiation into atmospheric heating. Solar energy absorbed by the ocean is withdrawn from the surface by evaporation. An equivalent amount of energy ( $78 \text{ W m}^{-2}$  averaged over the globe) is then given to the atmosphere when this same water condenses into clouds and rain. This transfer process is called the latent heat flux. Global-, annual-average values of the surface and atmosphere energy budget terms are shown in Fig. 1.1 (values taken from Kiehl and Trenberth 1997). The atmosphere is principally warmed by latent heating ( $LH(A)$ ) and cooled by infrared radiation ( $F(A)$ ). Conversely, the ocean is principally heated by solar radiation ( $S(0)$ ) and cooled by evaporation ( $LH(0)$ ).

Global mean values, however, say nothing about the equator-pole gradients alluded to above. The northern hemisphere meridional gradients of the atmospheric heat budget components are shown in Fig. 1.2a (values from Hartmann 1994) and indicate that warming peaks in the tropics. Net heating occurs in the tropics because precipitation, hence latent heating, dominates infrared cooling there. The converse is true near the pole, where latent



**Fig 1.2.** Northern hemisphere zonal-mean values of (a) atmospheric energy budget components (values from Hartmann 1994), (b) surface energy budget components (values from Sellers 1965), and (c) top-of-atmosphere cloud radiative forcing (CRF; values from Harrison et al. 1990). All values in  $\text{W m}^{-2}$ .

heating from precipitation is insufficient to balance infrared cooling. The corresponding meridional gradients of the surface heat budget components are shown in Fig. 1.2b (values from Sellers 1965). Surface absorption of solar energy in the tropics exceeds  $200 \text{ W m}^{-2}$ , roughly twice the cooling owing to evaporation. Thus, the heating gradient at the surface arises largely from the peak in solar incidence at the tropics, while the heating gradient in the atmosphere arises largely from the peak in latent heating in the tropics.

Infrared and solar radiation interact with atmospheric trace gases such as water vapor, carbon dioxide, and methane. In addition, clouds have an important impact on the flux of radiation through the atmosphere. The weak meridional gradient in atmospheric radiative cooling shown in Fig. 1.2a includes the contributions from all of these interactions. Cloud

radiative forcing (CRF), a simple means of separating the effect of clouds on the radiative energy budget (Ramanathan 1987), is the difference between the clear sky radiative fluxes and the cloudy sky fluxes. Shortwave cloud forcing ( $C_s$ ) is given by

$$C_s = S(\alpha_{clr} - \alpha), \quad (1.1)$$

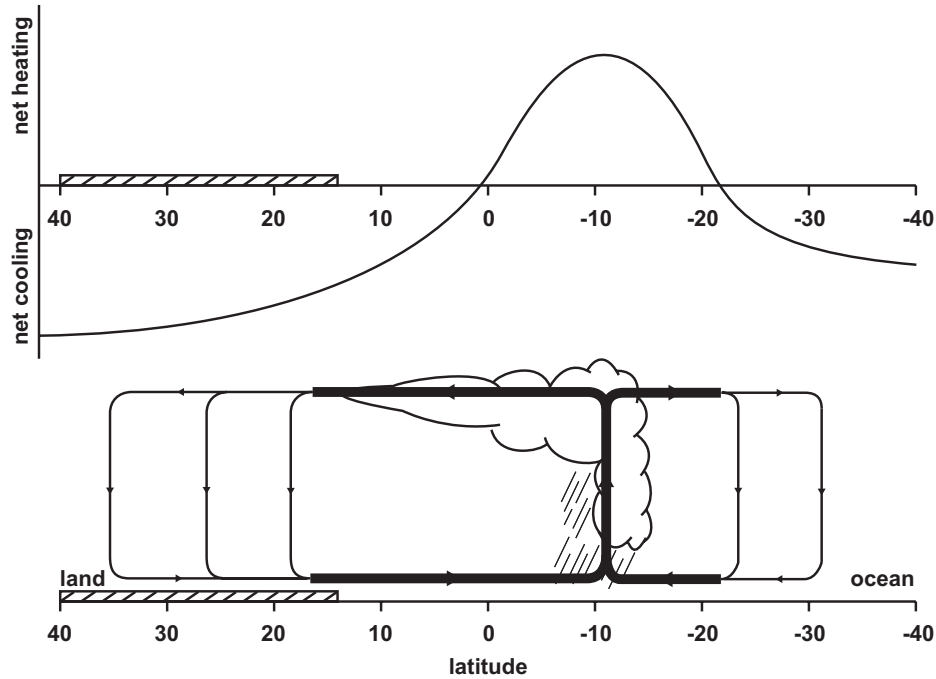
where  $S$  is the solar constant,  $\alpha_{clr}$  is the clear-sky albedo and  $\alpha$  is the all-sky albedo.

Longwave cloud forcing ( $C_l$ ) is given by

$$C_l = F_{clr} - F, \quad (1.2)$$

where  $F_{clr}$  is the clear-sky longwave flux to space and  $F$  is the all-sky longwave flux. When the approach was applied to the ERBE satellite observations (Ramanathan et al. 1989), it revealed that clouds have a net radiative cooling effect of about  $-20 \text{ W m}^{-2}$  (*i.e.*, the global average of the sum of  $C_l$  and  $C_s$  is  $-20 \text{ W m}^{-2}$ ). The meridional gradients of  $C_l$  and  $C_s$  at the top of the atmosphere are shown in Fig. 1.2c (data from Harrison et al. 1990). Local maxima in CRF occur in the tropics and the extra-tropical storm track. Ramanathan (1987) demonstrated that  $C_s$  in a GCM is expressed nearly entirely as a surface cooling, while  $C_l$  is expressed largely as a warming of the atmosphere. Thus the tropical peak in  $C_l$  suggests that longwave heating in tropical clouds enhances the equator to pole gradient in latent heating, while the peak in  $C_s$  suggests that the shortwave cooling effect reduces the solar heating gradient at the surface. Diagnostic and modeling studies (*e.g.*, Randall et al. 1989; Tian 2002) indicate that the gradient in  $C_l$  is instrumental in maintaining the observed thermal and moisture structure, as well as the circulation, of the tropical atmosphere.

The mean circulation over the Indian Ocean region during the winter monsoon is an example of the thermally-direct overturning circulation that results in the tropical atmosphere from heating gradients such as those discussed above (Fig. 1.3). Net heating in the convergence zone south of the equator gives rise to a narrow region of strong upward motion. The upward motion occurs through the process of atmospheric convection

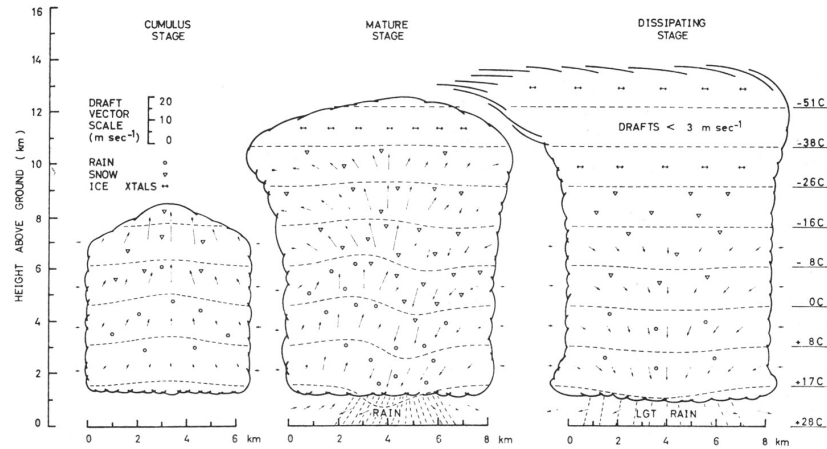


**Fig 1.3.** Schematic depiction of the net meridional heating structure, and the resulting circulation, over the Indian Ocean region during the winter monsoon (adapted from Webster 1987).

and is associated with precipitating cloud systems that contribute to the warming of the atmosphere through latent heating and longwave cloud radiative forcing. Net cooling away from the convergence zone is associated with broad, gentle subsidence. Such a circulation is characteristic of the time-mean dynamics of the tropical atmosphere in general. In the case of the monsoon, the strength of the heating gradient and the location of the convergence zone are further influenced by the properties of the south Asian landmass.

Evidence is now mounting that aerosol concentrations in the atmosphere are growing as a result of increasing pollution, and that the radiative impacts of the aerosols may be perturbing the energy balances described above (Ramanathan et al. 2001b). Solar radiation at the surface of the Indian Ocean was found to be reduced by  $-20 \text{ W m}^{-2}$  during the 1999 winter monsoon as a result of pollution from South Asia (Ramanathan et al. 2001a). A high concentration of dark carbonaceous aerosols was also linked to an atmospheric heating of



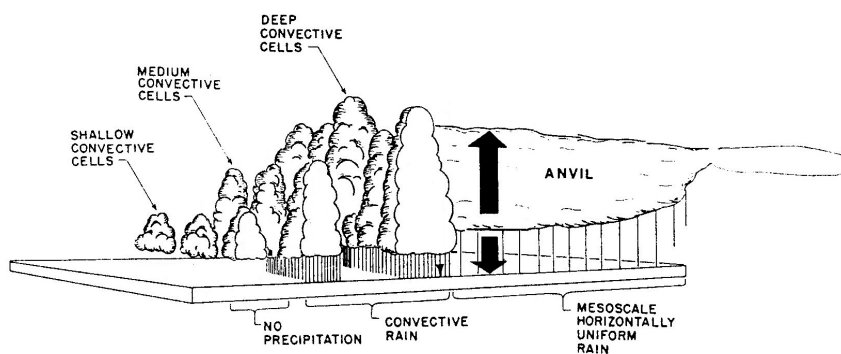


**Fig 1.4.** Three stages of development of a convective cell (from Chisholm 1973).

$+18 \text{ W m}^{-2}$ , owing to absorption of sunlight by the dark particles. The ability for regional sources of pollution to impact surface and atmospheric thermodynamics globally depends, in part, upon the efficiency of precipitating cloud systems to remove pollution and restrict long-range transport and mixing of aerosols.

## 1.2 The structure of precipitating tropical cloud systems

Although the general circulation of the tropical atmosphere is described above as being caused by the time- and space- averaged components of thermodynamic forcing, precipitation and cloud radiative forcing only occur in the presence of transient cloud systems. The quantities presented above are averages over contributions from numerous cloud systems. In regions of strong vertical motion, such as the wintertime tropical Indian Ocean, monthly-mean thermodynamic forcing is composed predominantly from contributions of a class of cloud system called a *mesoscale convective system* (MCS) (e.g., Cotton and Anthes 1989; Houze and Betts 1981). As shown in chapter 3, roughly 20 such cloud systems are present over the Indian Ocean at a time in order to maintain the mean latent heating of the winter monsoon circulation. MCS structure is closely linked to the amount of latent heating and cloud radiative forcing produced by the system, as well as the scale of the system.

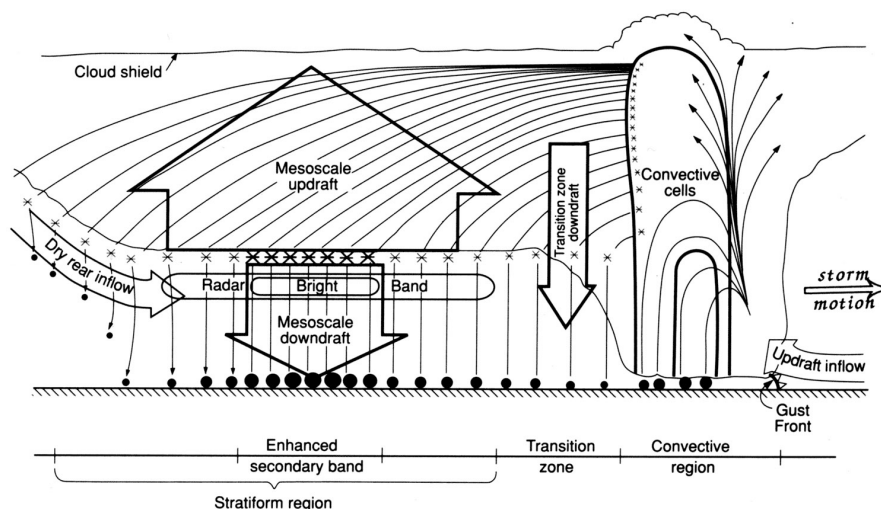


**Fig 1.5.** Schematic of a mesoscale convective system showing an ensemble of convective cells attached to stratiform anvil cloud and extended, non-precipitating cirrus cloud (from Houze et al. 1980).

A discussion of MCS structure is presented here.

The fundamental element of an MCS is the deep convective cell. Within a single cell, instability of warm moist air near the surface is released through the swift buoyant motion of air from the surface to the tropopause region (as high as 18 km in the tropics). Buoyancy is generated primarily through the rapid condensation of water into cloud drops (below the freezing level) and ice crystals (above the freezing level). Efficient coalescence of water and ice into rain, hail and graupel gives rise to strong rain rates at the surface. Evaporation of some of the precipitation as it falls within the cloud also gives rise to strong downdrafts adjacent to the convective updraft. Thus a single convective cell can be described as a narrow, vertically oriented overturning cell. A schematic of a convective cell is shown in Fig. 1.4. Aircraft studies indicate that convective cells have horizontal scales of 1 to 10 km (LeMone and Zipser 1980).

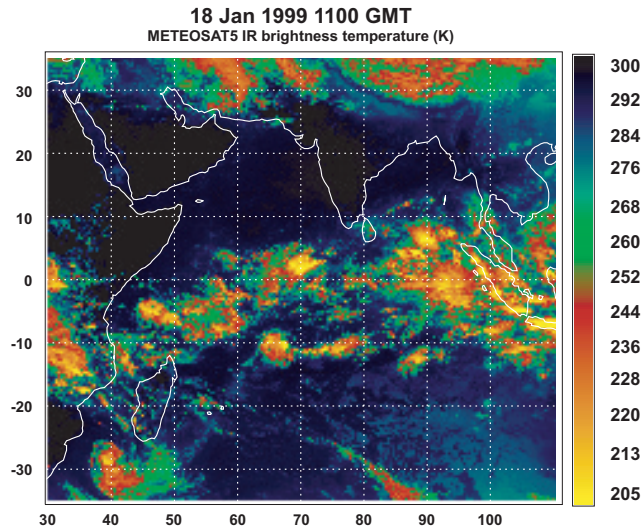
In MCSs, numerous convective cells group together within a single deck of cloud. As many as 10 may occur within a single MCS (Houze and Cheng 1977). At the tops of the convective cells large amounts of condensate detrain from the cells and spread horizontally. Therefore, adjacent to the region of deep convective cells, and within the same cloud deck, is a broad region of stratiform precipitation. The stratiform (sometimes called anvil) portion



**Fig 1.6.** Schematic cross section through a mesoscale convective system indicating hydrometeor trajectories through a line of convective cells with a trailing stratiform anvil (from Biggerstaff and Houze 1991).

of the MCS is characterized by an upper-level region of precipitating cloud with horizontal scales of 100-1000 km and rain rates typically much lower than in the convective cells. Condensation within the stratiform portion gives rise to gentle, mesoscale uplift within the anvil cloud deck (Fig. 1.5). Generally, cloud-free air occurs below the stratiform portion, however some precipitation falling from above typically evaporates. Evaporative cooling results in a gentle, mesoscale downdraft below the anvil cloud deck. Though the mesoscale updraft implies some condensation in the anvil cloud, as much as 75% of the stratiform precipitation may result from hail and graupel detraining horizontally from the upper portions of the convective cells (Gamache and Houze 1983). Fig. 1.6 indicates typical trajectories of precipitating drops and hail.

In satellite images of the tropics, such as Fig. 1.7, structures larger than 1000 km are apparent. The colors in Fig. 1.7 correspond roughly with the temperature at the top of the clouds. Dark blue regions are cloud-free while red and yellow regions indicate where clouds associated with active convection are present. As shown in chapter 4, it is not uncommon for giant decks of cloud spanning 1000s of km to be maintained by numerous



**Fig 1.7.** Infrared channel brightness temperature image (in K) from METEOSAT-5 from 18 Jan. 1999.

MCSs embedded within. Quantifying the spectrum of cloud systems that results from the hierarchy of convective structures described above is an important goal of this dissertation.

### 1.3 Cloud systems in atmospheric simulations

In order to perform simulations suitable for climate predictions, global climate models must account for the mass and momentum fluxes associated with the dynamics of tropical convection. Furthermore, the rate of condensation of rain drops must be predicted in order to calculate the magnitude of latent heating and the structure of the cloud decks must be predicted in order to calculate the cloud radiative forcing

Because of the fundamental role of latent heating and cloud radiative forcing in the planetary energy budget, global climate models must account for these processes, and anticipate changes in them resulting from greenhouse gas forcing, in order to perform simulations suitable for climate predictions. In the tropics, these processes are intimately related to atmospheric convection. Though the equations governing atmospheric dynamics in principle include the physics of convection, present day limitations in computing power prevent long-range, global climate predictions from being performed at sufficient resolution

to capture individual convective cells or even mesoscale anvil structures. All of the processes associated with a tropical cloud system residing within a grid cell are therefore computed using parameterizations that attempt to predict these quantities based on single, grid cell-averaged values of pressure, temperature, humidity and wind.

Much improvement remains to be made with respect to simulations of cloud systems in climate models. For example, an ensemble of convective cells occurring within a column of grid cells is typically predicted based on the column profile of instability (Arakawa and Schubert 1974). However cloud cover in a grid cell is often predicted based only on the grid cell value of relative humidity (Slingo 1987). The physical link between simulated convective dynamics and simulated cloud cover is weak in most models, in spite of the structure of tropical cloud systems being tightly coupled to convective dynamics. The assumption inherent in the present-day approach to cloud and convection parameterization is that all of the relevant processes occur at subgrid scales. As shown in chapter 3, however, the typical sizes of climate model grid cells are spanned by the spectrum of tropical cloud and precipitation structures, calling into question this assumption. Finally, the fluxes occurring in

## References

- Arakawa, A., and W. H. Schubert, 1974: Interaction of a cumulus cloud ensemble with the large-scale environment, part 1. *J. Atmos. Sci.*, **31**, 674-701.
- Biggerstaff, M. I. and R. A. Houze, Jr., 1991: Kinematic and precipitation structure of the 10-11 June 1985 squall line. *Mon. Wea. Rev.*, **119**, 3035-3065.
- Boer, E. R. and V. Ramanathan, 1997: Lagrangian Approach for Deriving Cloud Characteristics from Satellite Observations and its Implications to Cloud Parameterization. *J. Geophys. Res.*, **102**, 21,383-21,399.
- Cess, R. D. and co-authors, 1989: Interpretation of cloud-climate feedback as produced by 14 atmospheric general circulation models. *Science*, **245**, 513-516.
- Chisholm, A. J., 1973: *Alberta Hailstorms. Part I: Radar Case Studies and Airflow Models*. Meteor. Monograph, **14**, No. 36. American Meteorological Society, Boston, 36 pp.
- Cotton, W. R., and R. A. Anthes, 1989: *Storm and Cloud Dynamics*. Academic Press, San Diego,

CA, 883 pp.

- Gamache, J. F. and R. A. Houze Jr., 1983: Water budget of a mesoscale convective system in the tropics. *J. Atmos. Sci.*, **40**, 1835-1850.
- Harrison, E. F., P. Minnis, B. R. Barkstrom, V. Ramanathan, R. D. Cess, and G. G. Gibson, 1990: Seasonal variation of cloud radiative forcing derived from the Earth Radiation Budget Experiment. *J. of Geophys. Res.*, **95**, 18,687-18,703.
- Hartmann, D. L., 1994: *Global Physical Climatology*, Academic Press, San Diego, CA, 411 pp.
- Houghton, J. T., Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden, and D. Xiaosu, Eds., 2001: *Climate Change 2001: The Scientific Basis: Contribution of Working Group 1 to the Third Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, 944 pp.
- Houze, R. A., Jr., and C.-P. Cheng, 1977: Radar characteristics of tropical convection observed during GATE: Mean properties and trends over the summer season. *Mon. Wea. Rev.*, **105**, 964-980.
- Houze, R. A., Jr., and C.-P. Cheng, C. A. Leary, and J. F. Gamache, 1980: Diagnosis of cloud mass and heat fluxes from radar and synoptic data. *J. Atmos. Sci.*, **37**, 754-773.
- Houze, R. A., Jr., and A. K. Betts, 1981: Convection in GATE. *Rev. Geophys. Space Phys.*, **19**, 541-576.
- Kiehl, J. T. and K. E. Trenberth, 1997: Earth's annual global mean energy budget. *Bull. Am. Meteorol. Soc.*, **78**, 197-208.
- LeMone, M. A. and E. J. Zipser, 1980: Cumulonimbus vertical velocity events in GATE. Part I: Diameter, intensity and mass flux. *J. Atmos. Sci.*, **37**, 2444-2457.
- Machado, L. A. T. and W. B. Rossow, 1993: Structural characteristics and radiative properties of tropical cloud clusters. *Mon. Wea. Rev.*, **121**, 3234-3260.
- Ramanathan, V., 1987: The role of Earth radiation budget studies in climate and general circulation research. *J. of Geophys. Res.*, **92**, 4075-4095.
- Ramanathan, V. R. D. Cess, E. F. Harrison, P. Minnis, B. R. Barkstrom, E. Ahmad, and D. Hartmann, 1989: Cloud-radiative forcing and climate: Results from the Earth Radiation Budget Experiment. *Science*, **243**, 57-63.
- Ramanathan, V. and co-authors, 2001a: Indian Ocean Experiment: An integrated analysis of the climate forcing and effects of the great Indo-Asian haze. *J. Geophys. Res.*, **106**, 28,371-28-398.

- Ramanathan, V., P. J. Crutzen, J. T. Kiehl, and D. Rosenfeld, 2001b: Aerosols, Climate and the Hydrological Cycle. *Science*, **294**, 2119-2124.
- Randall, D. A., T. G. Corsetti, Harshvardhan, and D. A. Dazlich, 1989: Interactions among radiation, convection, and large-scale dynamics in a general circulation model. *J. Atmos. Sci.*, **46**, 1943-1970.
- Sellers, W. D., 1965: *Physical Climatology*, University of Chicago Press, Chicago, IL, 272 pp.
- Slingo, J. M. 1987: The development and verification of a cloud prediction scheme for the ECMWF model. *Quart. J. Roy. Meteor. Soc.*, **113**, 899-927.
- Tian, B., 2002: *Cloud Radiative Forcing and the Tropical Hadley and Walker Circulations*. Ph.D. dissertation, Scripps Institution of Oceanography, University of California, San Diego.
- Webster, 1987: The elementary monsoon, in *Monsoons* (J. Fein and P. Stephens, Eds.), John Wiley & Sons, New York, 632 pp.
- Williams, M. and R. A. Houze, Jr., 1987: Satellite-observed characteristics of winter monsoon cloud clusters. *Mon. Wea. Rev.*, **115**, 505-519.